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A group of galaxies around the giant spiral NGC 6946

I.D.Karachentsev[1], **M.E.Sharina**[1], **and W.K.Huchtmeier**[2]

[1] Special Astrophysical Observatory, Russian Academy of Sciences, N.Arkhyz, KChR, 369167, Russia
[2] Max-Plank-Institut für Radioastronomie, Auf dem Hügel 69, 53121, Bonn, Germany

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Abstract. We present large-scale CCD images of a dozen low surface brightness objects in the vicinity of giant Sc galaxy NGC 6946, which have been found recently on POSS-II copies. Six of them: UGC 11583, kk251, kk252, kkr55, kkr56, and kkr59 are dwarf irregular galaxies resolved into stars. We determined their distances from the luminosity of the brightest blue stars. The mean estimated distance to the NGC 6946 group is 5.9±0.4 Mpc. Together with Cepheus 1, discovered before, the group consist of 8 late type galaxies. Almost all of them are detected or marginally detected in the HI line. The group is characterized by a linear projected diameter of 420 kpc, a radial velocity dispersion of 95 km s^{-1}, and a virial mass-to-luminosity ratio about 56 $M_\odot/L_\odot$.

Key words: galaxies: distances — galaxies: irregular — galaxies

1. Introduction

NGC 6946 is amongst the seven more massive galaxies in the Local Volume (=LV) with distances $D < 7$ Mpc (Karachentsev et al. 1999). 51% of the population of the LV are within the gravitational influence of these "oligarchs". Each of 7 the giant galaxies, except NGC 6946, has a lot of dwarf companions: from 7–9 members around Sc galaxies M101 and NGC 5236 to 32 members around giant elliptical galaxy NGC 5128. In this sense the absence of accompying dwarf systems around NGC 6946 within a radius of ∼1 Mpc (Tully, 1988) looked like a remarkable anomaly. However, the apparent isolation of NGC 6946 may be related with its location on a border of the Local Void (Tully 1988). The substantial galactic extinction in the direction of NGC 6946 has also an influence on the visibility of faint dwarf galaxies.

Based on copies of the Second Palomar Observatory Sky Survey (=POSS-II), Karachentseva & Karachentsev (1998) undertook a search for galaxies of low surface brightness in the vicinity of normal galaxies in the LV. Observations of these galaxies (kk- list) with the 100-m Effelsberg radio telescope revealed three dwarf galaxies: UGC 11583 = kk250, kk251, and kk252, with positions and radial velocities close to NGC 6946 (Huchtmeier et al. 1997). Using the luminosity of the brightest stars in NGC 6946 and UGC 11583, Sharina et al. (1997) derived distance moduli to these galaxies: 28.90 and 29.13 mag, respectively. During the course of a search for compact high velocity clouds Burton et al. (1999) discovered beside NGC 6946 a low surface brightness galaxy with radial velocity $V_h = +58$ km s^{-1} named by them Cepheus 1. Subsequent searches for nearby dwarf galaxies by Karachentseva et al. (1999) (kkr- list) and Karachentseva et al. (2000) (kkh- list) led to the discovery of some more LSB objects around NGC 6946. In this paper we present results of optical and HI observations of these new objects, particularly data on three new probable companions of NGC 6946.

2. Optical observations and photometry

Table 1 lists 18 nearby dwarf galaxy candidates from the above mentioned list with projected distances to NGC 6946 of less than 1 Mpc. For the giant galaxy NGC 6946, also included in the Table, a distance of 5.9 Mpc (see Sect.4) is adopted. Besides the galaxy name, and its equatorial and galactic coordinates, Table 1 contains: major and minor axes measured on the blue (J) POSS-II copy, morphological type determined with with POSS-II copies, surface brightness (low, very low, extremely low), and galactic extinction in the B, and I bands according to Schlegel et al.(1998).

The HI line observations showed that objects kkr46, kkr48, and kkr58 are background galaxies with heliocentric radial velocities of respectively +3779, +3158, and +2756 km s^{-1}. Images of the remaining 15 objects from the Digital Sky Survey are reproduced in Figure 1, each field being 5 arcmin wide .

Most objects were imaged with the 6-m telescope (Russia) and the 2.5-m Nordic telescope (Spain) in different filters of the Johnson-Cousins system. Table 2 presents the observational log with indication of exposure time and seeing. A 1k×1k CCD detector was used at the 6-m telescope, providing a total view of 3.′5 with a resolution of 0.″21/pixel.

Fig. 1. Digital Sky Survey images of 15 dwarf galaxy candidates in the vicinity of NGC 6946. The field size is 5′, North is to the top, and East is to the left.

Table 1. List of dwarf galaxy candidates around NGC 6946 within projected radius of ∼1 Mpc.

Name	RA (2000.0)	DEC	L, B		$a \times b$		Type		A_B	A_I
kkr46	$19^h36^m36^s.2$	54°38′21″	86.8°	15.7°	0′.8	0′.6	Ir	L	0.456	0.205
kkh90	19 41 50.6	68 34 14	100.5	20.7	1.3	0.75	Ir?	VL	0.673	0.303
kkr48	19 57 56.4	62 37 21	95.5	16.7	0.9	0.45	Ir	L	0.359	0.162
kkh92	20 10 01.1	66 05 01	99.4	17.2	0.5	0.2	Ir	L	1.414	0.636
kkr51	20 21 15.5	52 28 03	88.2	8.9	0.7	0.35	Ir	L	1.152	0.518
kk250	20 30 15.0	60 26 31	95.6	12.3	1.8	0.8	Ir	VL	1.319	0.593
kk251	20 30 32.9	60 21 13	95.6	12.2	1.6	0.8	Ir?	VL	1.236	0.556
kk252	20 31 33.1	60 48 48	96.0	12.4	0.9	0.9	Sph?	VL	1.913	0.860
kk254	20 34 45.7	61 05 37	96.5	12.2	1.5	0.9	Ir?	EL	1.936	0.870
N6946	20 34 51.9	60 09 15	95.7	11.7	11.0	10.0	Sc	-	1.475	0.663
kkr55	20 45 20.8	60 24 40	96.7	10.8	0.6	0.4	Ir	L	2.941	1.322
kkr57	20 47 32.6	63 04 10	99.0	12.2	0.5	0.45	Ir	L	1.444	0.649
kkr56	20 48 24.1	58 37 06	95.5	9.4	0.7	0.45	Ir	L	3.135	1.409
kkr58	20 49 33.7	58 06 18	95.2	8.9	2.1	0.2	Sm	VL	3.635	1.634
Ceph1	20 51 10.7	56 53 25	94.4	8.0	3.0:	1.5:	Sm?	VL	4.047	1.819
kkh93	20 57 59.5	62 20 56	99.2	10.8	0.5	0.35	Ir	L	2.891	1.300
kkr59	21 03 24.2	57 17 14	95.8	7.0	2.3	1.4	Ir	VL	3.863	1.737
kkr60	21 05 53.0	57 12 19	95.9	6.7	0.7	0.5	Ir	VL	4.574	2.056
kkr62	21 30 44.9	52 41 39	95.2	1.0	1.1:	0.6:	Ir?	EL	12.062	5.423

Fig. 2. CCD images of twelve LSB objects around NGC 6946: a) kkh90, b) kkh92, c) kk250= UGC 11583, d) kk251, e) kk252, f) kk254, g) kkr55, h) kkr57, i) kkr56, j) kkh93, k) kkr59, and l) kkr62. All of them, except kk252, were observed with the 6-m telescope. On each frame a scale is indicated with a 10″ bar.

The observations at the Nordic telescope were performed with a 2k×2k CCD providing a field of 3′.7 with a resolution of 0″.22/pixel after 2×2 rebinning. The images were processed with the DAOPHOT II program (Stetson et al. 1998) implemented in MIDAS. Standard stars from Landolt (1992) were used for calibration. In cases where galaxies are resolved into stars we derived colour-magnitude diagrams for stars in the galaxy and in surrounding field. Besides stellar photometry we also carried out aperture photometry of the galaxies in circular apertures that allows the total integral magnitudes and surface brightness profiles to be measured. The luminosity of the brightest stars was used to determine distances. Below we consider each object in more detail.

kkh90. The R- band image of this object is shown in Fig. 2a. The object has a hook shape and is unresolved into stars to the limiting magnitude R∼24 mag. It is undetected in the HI line. kkh90 is very probably an isolated fragment of a faint reflexion nebula.

kkh92. In Fig. 2b kkh92 looks like a distant galaxy, which has an elongated central part (bar?) surrounded with a LSB envelope (disk?). Its HI spectrum shows no emission within [−500, +4000] km s^{-1}.

UGC11583 = kk250. This irregular dwarf galaxy has been discussed by Sharina et al. (1997) as a companion of NGC 6946. Fig. 2c presents its R image derived with a seeing of FWHM = 1″.1. According to Schlegel et al. (1998) the galactic extinction in the direction of UGC 11583, A_B = 1.32 mag, is lower than adopted before (1.93 mag), increasing its distance modulus.

kk251. Its angular separation from the previous galaxy is only 6′, less than the half power width (9′.3) of the 100-m radio telescope. The similarity of their radial velocities, +127 and +126 km s^{-1} may be the result of HI flux confusion. However, Fig. 2d suggests that kk251 is a nearby irregular galaxy resolved into stars. Its distance estimate (see below) is in agreement with membership in the NGC 6946 group. The integral magnitude of kk251, B_T = 16.49, has been measured by Hopp (1998).

kk252. A rather bright red star is projected into the western side of the galaxy (Fig. 2e). Judging on its radial velocity, V_h = +132 km s^{-1}, this well- resolved irregular galaxy is a companion of NGC 6946.

kk254. The apparent structure of this object (Fig. 2f) definitely shows that it is a small reflexion nebula. Such isolated cirrus with very low surface brightness can easily

Table 2. Observational log

Object	Date	Telescope	Filter	Exposure	Seeing	Comments
kkh90	18.06.99	BTA	V	600s	1.0	cirrus
			I	600		
kkh92	10.07.99	BTA	R	300	1.1	distant
	06.11.99	BTA	R	600	2.0	
			I	600		
kk250=	10.07.99	BTA	R	300	1.1	resolved
U11583						
kk251	26.07.97	NOT	I	600	0.6	resolved
	10.07.99	BTA	R	300	1.1	
	10.07.99		I	300		
kk252	28.07.97	NOT	V	900	0.7	resolved
			I	600		
kk254	26.07.97	NOT	I	600	0.7	cirrus
	10.07.99	BTA	R	300	1.1	
			I	300		
kkr55	09.07.99	BTA	V	600	1.2	resolved
			R	300		
			I	300		
kkr57	09.07.99	BTA	V	600	1.2	semi-resolved
			R	300		
kkr56	09.07.99	BTA	R	300	1.2	resolved
			I	300		
kkr58	10.07.99	BTA	R	300	1.1	distant edge-on RFGC galaxy
kkh93	10.07.99	BTA	R	300	1.1	distant
	06.11.99	BTA	R	600	2.0	
			I	600		
kkr59	10.07.99	BTA	R	300	1.1	resolved
			I	300		
kkr62=	06.11.99	BTA	R	900	2.5	PN/RN ?
Dw95+1			I	900		

be confused with an irregular galaxy. The object is undetected in HI.

kkr55. This compact irregular galaxy is well resolved into stars (Fig. 2g). The brightest stars beside its center are embedded into a diffuse envelope suggesting a starburst region. The galaxy is undetected in the HI line, but its HI emission is probably merged with the strong emission of the local galactic hydrogen (see below).

kkr57. The central part of the galaxy has an asymmetric, skewed shape (Fig. 2h). Apparently kkr57 is not resolved into stars but into compact knots. It is unclear why such a blue irregular galaxy is undetected in HI. Spectral observations of the object in the H alpha line may clarify its nature.

kkr56. As it is seen from Fig. 2i, this irregular galaxy is well resolved into stars. In spite of its marginal detection in the HI line, kkr56 seems to be a true companion of NGC 6946. This should be confirmed by observations in H alpha.

kkh93. This galaxy is undetected in HI. Probably, it is a medium distant Sm galaxy (Fig. 2j).

kkr59. On POSS-II plates this irregular galaxy looks like a planetary nebula. Its large-scale image, Fig. 2k, reveals a lot of faint stars, as well as several probable compact HII regions on the northern side of the galaxy. A marginal detection of kkr59 in the HI line needs to be confirmed by optical spectroscopy.

kkr62. This object was imaged under bad seeing (Fig. 2l). It is located in a zone of very high extinction ($A_B \sim$ 12 mag!) near the HI- source Dwingeloo 095+1.0 with a velocity of $V_h = +159$ km s^{-1} (Henning et al. 1998). kkr62 has an extremely low surface brightness in the R band and is practically unseen in the I band. It might be a planetary nebula or a small reflexion nebula.

3. HI observations

All the objects in Table 1 were observed in the HI 21 cm line using the 100-m radio telescope at Effelsberg (HPBW= 9′.3). Observations have been obtained in the total power mode combining the on-source position with a reference field. A velocity resolution of about 5 km s^{-1} was achieved after Hanning smoothing. The search range was [−500, +4000] km s^{-1}. As mentioned above, three dwarf irregular galaxy: kk250, kk251, and kk252 have been detected before (Huchtmeier et al. 1997). For three other dwarfs: kkr55, kkr56, and kkr59, the HI line profiles are presented in Fig. 3.

The main difficulty of detection in the HI line of galaxies around NGC6946 is caused by their low radial velocities which are expected to be in the range of [−150, +250] km s^{-1}. As seen from Fig. 3 as well as Fig. 1 of Burton et al. (1999), the galactic hydrogen emission is predominant in the velocity range of about [−100, 0] km s^{-1}. It 'hides' almost completely weak emission from galaxies with velocities in the indicated range, and leads to an asymmetric distribution of the group members according to their velocities. We find a similar situation in two other nearby groups, M81 and IC342/Maffei (van Driel et al. 1998, Huchtmeier et al. 2000).

Table 4. Observed properties of galaxies in the NGC 6946 group

Parameter	N6946	kk250	kk251	kk252	kkr55	kkr56	Ceph1	kkr59
Type	Sc	Ir	Ir	Ir	Ir	Ir	Sm	Im
B_T	9.7	15.7	16.5	16.7	17.0	17.6	15.4	15.7
A_B	1.48	1.32	1.24	1.91	2.94	3.14	4.05	3.86
$(B-V)_{T,0}$	0.55	—	0.79:	0.47	0.29	0.44	0.3:	0.38
$< B(3B) >_{3,0}$	19.34	21.70	21.37	21.22	20.96	21.37	—	19.98
$< B-V >_{3,0}$	−0.02	0.30	0.07	−0.21	0.27	0.13	—	−0.28
$(m-M)_0$	29.15	29.57	28.63	28.64	28.66	29.04	[28.89]	28.34
D, Mpc	6.8	8.2	5.3	5.3	5.4	6.4	[6.0]	4.7
$M_{B,0}$	−20.6	−14.5	−13.6	−14.1	−14.8	−14.4	−17.5	−17.0
V_h, km s^{-1}	+51	+127	+126	+132	+23?	−135:	+58	+17:
V_o, km s^{-1}	+343	+430	+429	+435	+330?	+172:	+374	+327:
W_{50}, km s^{-1}	169	90	64	27	44?	10:	90	63:
F, Jykm s^{-1}	839	20	14.6:	1.36	1?	5.6:	136	36:
$M(HI)/L_B$	0.26	1.86	3.02:	0.18	0.07?	0.56	0.76	0.32
$r,^\circ$	0	0.64	0.57	0.78	1.35	2.31	3.90	4.68
R, kpc	0	66	59	81	139	239	403	483

In the case of kkr55 the situation seems to be very complicated. A weak emission feature with $V_h = 23$ km s^{-1}, a line width W_{50} ∼44 km s^{-1}, and a flux F ∼1 Jy km s^{-1} is suspected. Radio observations with an aperture synthesis telescope or optical spectra may help to verify this feature. In the HI line spectrum of kkr56 we note possible weak emission with parameters: $V_h = -135$ km s^{-1}, $W_{50} = 10$ km s^{-1}, and $F = 5.6$ Jy km s^{-1}. The third galaxy, kkr59, has probably emission with $V_h = +17$, $W_{50} = 63$, and $F =$ 36 Jy km s^{-1} adjacent to the Local HI emission. All three HI detections are marginal and have to be confirmed with independent optical/radio observations.

Table 3. Apparent magnitudes of the observed galaxies

Galaxy	I_T	$R_T - I_T$ $[V-I]_T$	I_c	h''
kkh92	15.58	0.62	22.1	9
kk251	14.42	0.78	22.8	21
kk252	14.16	[1.41]	21.0	7
kkr55	14.57	0.73	21.5	10
kkr56	14.69	0.91	22.5	11
kkh93	15.41	0.72	21.4	5
kkr59	12.52	0.98	22.5	40

4. Photometry results and distances

Results of our surface photometry of 7 galaxies around NGC 6946 are presented in Table 3. Its columns contain: (1) galaxy name, (2) integral apparent magnitude in the I band, (3) integral colour $R-I$ or $V-I$, (4) central surface brightness in the I band, (5) exponential scale lenght in arcsec. To estimate the integral blue magnitude of a galaxy we used the transformation $(B-V)_0 = 0.85 \cdot (V-I)_0 - 0.20$, derived by Makarova (1999) for late type galaxies. When only the integral colour $R-I$ is measured, we used an approximate relation $(R-I)_0 = 0.48(V-I)_0$ after dereddening.

Based on photometry of the brightest stars in the galaxies: kk251, kk252, kkr55, kkr56, and kkr59 we determine the mean apparent magnitude of the three brightest blue stars, $< B(3B) >$, and use it as an indicator of distance to the galaxies. According to Sandage & Tammann (1974) and de Vaucouleurs (1978) the mean luminosity of blue supergiants in a late type galaxy depends on its integral magnitude B_T. After calibration with cepheids, this relation can be written (Karachentsev & Tikhonov, 1994) as

$$(m-M)_0 =< B(3B) > -A_b + 0.51[< B(3B) > -B_T] + 4.14.$$

In order to obtain B magnitudes from V or R we used the empirical relations:

$$(R-I)_0 = 0.48(V-I)_0,$$

$$(B-V)_0 = 0.89(V-I)_0,$$

determined via standard Landolt's stars with colours $(B-V)_0 < 1$. The derived distance moduli are presented in Table 4, which contains the basic integral parameters of the galaxies. In this Table we incuded also data on Cepheus 1 from Burton et al. (1999), as well as data on NGC6946 and kk250 from Sharina et al. (1997) with the corrections for extinction from Schlegel et al. (1998). In this Table the rows indicate the following parameter: (1) morphological type, (2) integral galaxy magnitude, (3) adopted value of extinction; (4) integral galaxy colour corrected for extinction; (5,6) the mean apparent magnitude and the mean colour of the three brightest blue stars, corected for redening, (7,8) derived distance modulus and linear distance in

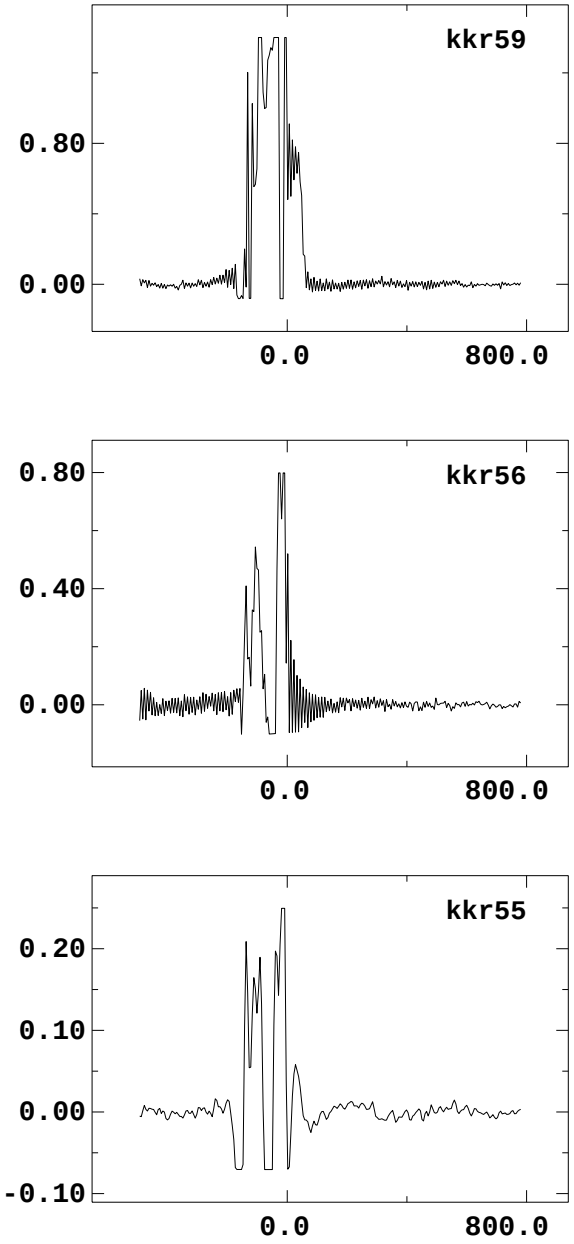

Fig. 3. HI spectra of the galaxies: a) kkr55, b) kkr56, and c) kkr59, obtained with the 100-m Effelsberg radio telescope.

Mpc; (9) absolute magnitude assuming the mean modulus of $< m - M >_0 = 28.86$; (10,11) heliocentric velocity and velocity reduced to the Local Group centroid; (12) the HI line width at a 50% level of the maximum; (13) the HI line flux; (14) hydrogen mass-to-luminosity ratio in solar units; (15,16) angular and linear projected separation from NGC 6946.

5. Properties of the NGC 6946 group

In spite of substantial extinction towards the NGC 6946 group and of the indirect estimate of blue magnitudes of member stars, the derived distance moduli of the candidate group members agree satisfactorily. Assuming a distance modulus of 28.89 for Cepheus 1 (Burton et al. 1999) from the luminosity of its HII regions, the mean distance modulus for eight members of the group is 28.86±0.14 with a standard deviation of 0.36 mag, typical for distances using the brightest stars. With a mean distance of 5.9±0.4 Mpc, the absolute magnitudes of dwarf irregular companions of NGC 6946 lie in a usual range of [−13.6, −17.5]. Probably the group contains also fainter members,

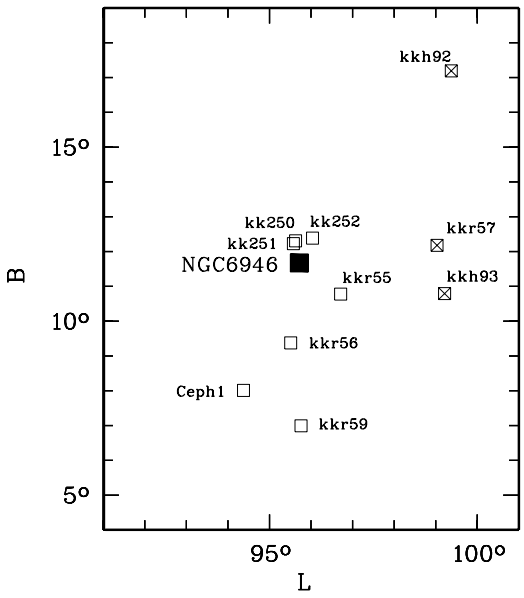

Fig. 4. The distribution of LSB objects around NGC 6946 (full squares) in galactic coordinates. The open squares represent the members of the NGC 6946 group, the squares with cross correspond to other probable group members.

but a search for them would be a rather difficult observational task. Besides kk251, where the estimate of $(B-V)_T$ is complicated by a superposition of bright stars, the companions of NGC 6946 have colours typical for irregular galaxies.

Adopting the above identifications of HI emission in galaxies, we obtain hydrogen mass-to-luminosity ratios

within [0.18 – 3.0] $M_\odot/L_\odot$, which is also typical for irregular galaxies. The hydrogen mass is obtained from the HI flux, F (in Jy·km s^{-1}), and distance D (in Mpc), as

$$\log[M(HI)/M_\odot] = \log F + 2\log D + 5.37.$$

The mean square radial velocity of companions with respect to NGC 6946 is 95 km s^{-1}, and their mean relative velocity is (+8±41) km s^{-1}. Fig. 4 shows the location of seven physical companions of NGC 6946 (open squares) in galactic coordinates. Three other galaxies in the same area without radial velocities and distance estimates are indicated with crosses. The most distant group member, kkr59, is at 483 kpc from NGC 6946. This is approximately the same size as that of the systems of companions we see around other near giant spiral galaxies: M31, M81, and M101. Based on the mean linear separation of dwarf galaxies in the NGC 6946 group, $< R > = 210$ kpc, and their root mean square radial velocity, 95 km s^{-1}, we can estimate a virial mass of the group. In case of randomly orientated closed orbits with a mean orbit eccentricity of $e = 0.5$ the virial (orbital) mass is $1.6{\cdot}10^{12} M_\odot$. Since the integral blue luminosity of the group is $2.9{\cdot}10^{10} L_\odot$, it yields a virial mass-to- luminosity ratio $\sim 56 M_\odot/L_\odot$, typical for small galaxy groups like the Local Group.

6. Concluding remarks

Being located at a low galactic latitude, $b = 12°$, in a zone of substantial extinction, NGC 6946 looks at first glance like an isolated giant spiral galaxy on the border of the Local Void (Tully, 1988). Recent searches for low surface brightness galaxies on the POSS-II films revealed about a dozen probable companions to NGC 6946. Subsequent HI observations of the candidates and distance estimates from the brightest stars showed that at least 7 dwarf irregular galaxies can be considered as physical companions of NGC 6946. Therefore, a new nearby group of galaxies has been discovered at a distance of (5.9±0.4) Mpc. The mean projected diameter of the group is 420 kpc, its root mean square radial velocity is 95 km s^{-1}, and the virial mass-to-luminosity ratio is $\sim 56 M_\odot/L_\odot$, typical for small galaxy groups. The two nearby giant face-on Sc galaxies: M101 and NGC 6946, and their dwarfs are alike with respect to their structure and kinematics. Being gas-rich galaxies, the members of the NGC 6946 group need to be studied in more detail with radio HI synthesis interferometry.

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